Sinonasal outcomes on nasal acoustics and resonance (SONAR)*

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Dear Editor:

The nasal and paranasal cavities constitute integral components of the vocal tract resonator system, yet their precise contribution to voice quality remains a subject of debate. While early anatomical and acoustic models [(1-3)] suggested that sinus coupling through open ostia may introduce anti-resonances and spectral alterations, subsequent investigations employing cadaveric dissections, physical simulations, and three-dimensional replicas [(4, 5)] have confirmed notable effects on frequency response and formant balance. Clinical studies, including those examining patients with chronic rhinosinusitis undergoing functional endoscopic sinus surgery (FESS), have shown that surgical management can improve both sinonasal and vocal quality of life without adverse effects on voice characteristics [(6,7)]. However, conventional acoustic measures such as jitter and shimmer frequently fail to detect such changes [(8)]. In contrast, Mel-frequency cepstral coefficients (MFCCs), which transform the speech spectrum into a perceptually weighted domain, have shown superior sensitivity to resonance-related shifts and hypernasality [(9)]. Based on this evidence, we investigated whether MFCCs and spectral flatness can more accurately identify post-operative alterations in resonance that are not captured by traditional acoustic parameters.

This prospective study included adults diagnosed with chronic rhinosinusitis scheduled for FESS, with pre- and one-month postoperative evaluations consisting of voice recordings and validated questionnaires (SNOT-22, NOSE, and VHI-10). Exclusion criteria included prior voice disorders, professional voice training, dysphonia, vocal fold paralysis, speech disorders, or hearing impairment. Voice samples were collected in a standardized setting using a high-fidelity recording system, capturing sustained vowels (/a/, /i/, /u/, /o/, /e/) and nasal sounds (/n/, /m/). Recordings were segmented and processed using Praat for formant analysis and Librosa for spectral feature extraction, including MFCCs, spectral centroid, and flatness. Surgical interventions varied from isolated procedures to full-house FESS, with additional septoplasty or turbinectomy as indicated. CT imaging was scored using the Lund-Mackay system. Statistical analyses were conducted using Jamovi and Python, applying both parametric and non-parametric tests with significance set at $p = 0.05$, and correction for multiple comparisons across MFCC values. Power analysis determined a minimum of 15 participants was required; the final cohort of 23 patients provided sufficient power to detect clinically meaningful within-subject changes in acoustic and subjective outcomes.

Of the 38 patients initially enrolled, 23 completed both pre- and postoperative assessments and were included in the final analysis (mean age 42.3 ± 18.0 years; 56.5% female; 17.4% with prior sinus surgery). Significant symptomatic improvements were observed one month after FESS, with mean SNOT-22, NOSE, and VHI-10 scores decreasing markedly, reflecting improved sinonasal function, nasal airflow, and voice-related quality of life. Acoustic analysis showed a significant reduction in shimmer and an increase in HNR (Harmonics-to-Noise Ratio), while jitter and formant frequencies remained unchanged. In contrast, several MFCCs (MFCC4, MFCC10, and MFCC13) demonstrated statistically robust postoperative changes, with MFCC13 emerging as the most sensitive marker of resonance improvement (Figure 1A, 1B, 1C). Spectral flatness also improved significantly (Figure 1D), reflecting modifications in harmonic voice structure. Subgroup analysis revealed that patients with bilateral disease showed more consistent changes in spectral flatness and MFCC4, whereas those with unilateral disease demonstrated greater variability, with more pronounced shifts in MFCC13.

In conclusion, FESS results in significant improvements in sinonasal symptoms, nasal airflow, and voice-related quality of life, accompanied by measurable acoustic changes. While traditional parameters such as jitter and formants showed limited sensiti-

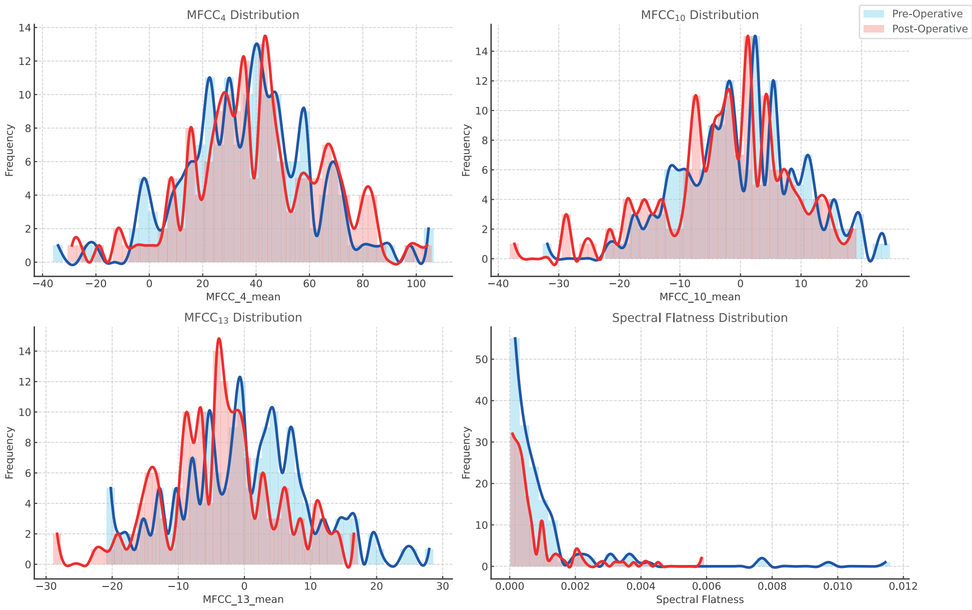

Figure 1. Histograms of significant acoustic features comparing Pre- and Post-FESS outcomes. The plots illustrate the frequency distributions of significant MFCCs and Spectral Flatness for pre-operative (blue) and post-operative (red) conditions. The panels display the distributions for MFCC4 (top left), MFCC10 (top right), MFCC13 (bottom left), and Spectral Flatness (bottom right).

vity, shimmer, HNR, spectral flatness, and especially MFCCs provided robust indicators of postoperative resonance shifts. These results highlight the added value of MFCC-based analysis in capturing subtle spectral changes not detected by conventional metrics, highlight the utility of MFCC-based analysis as a sensitive tool for detecting subtle postoperative spectral changes not captured by traditional acoustic metrics.

Authorship contribution

NB and IS conceived and designed the study. NB, FJ, and MD collected the data. IS performed the acoustic and statistical analyses. NB and IS drafted the manuscript. IB contributed to study supervision and critical revision of the manuscript. All authors reviewed and approved the final version.

Conflict of interest

The authors declare no conflicts of interest related to this work.

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SUPPLEMENTARY MATERIAL

Materials and Methods

This prospective study included patients diagnosed with chronic rhinosinusitis who were scheduled to undergo functional endoscopic sinus surgery (FESS). The study included all patients aged 18 years or older who agreed to participate and completed both preoperative and post-operative evaluations. Voice recordings and self-reported outcomes were collected pre-surgery and approximately one-month post-surgery. Although later timepoints may reflect more stable healing, the one-month postoperative assessment was chosen to capture early functional and resonance changes occurring during the initial phase of mucosal recovery. This timing also accounted for logistical considerations, including patients' ability to return for follow-up within the framework of national healthcare regulations, such as insurance approval processes for postoperative evaluations. All FESS procedures were performed by one of four experienced surgeons participating in the trial.

Inclusion and exclusion criteria

Participants were eligible if they were at least 18 years old, had a diagnosis of chronic rhinosinusitis, and were scheduled for FESS. They must have no history of professional voice training or previous voice pathologies requiring therapy. Additionally, patients with any dysphonia, vocal fold paralysis, speech disorder, or hearing impairment were excluded. All participants gave written informed consent, and the study was approved by the Hillel Yaffe Medical Center ethics committee (0025-23-HYMC).

Data collection

Voice data were recorded in a quiet room to minimize background noise interference. Participants were seated 50cm from the microphone for consistency. Recordings were obtained using a Galaxy S6 tablet (Samsung, Korea) connected to a Blue Yeti USB microphone set to cardioid mode for focused, directional, high-quality recording. The WavePad app (version 19.6, NCH Software, Australia) was used to capture audio in uncompressed WAV format, ensuring high fidelity for further analysis.

Recording procedure

Patients were recorded producing sustained phonations of the vowels /a/, /i/, /u/, /o/, /e/ as well as the nasal sounds /n/ and /m/. The exact same set of utterances was collected during both preoperative and post-operative sessions. Recordings were segmented into individual vowel/nasal segments using Audacity (version 3.6) on OSX.

Questionnaires and imaging

Patients completed three validated questionnaires pre- and post-operatively: the Sinonasal Outcome Test (SNOT-22), the Nose Score Test (NOSE), and the Voice Handicap Index (VHI-10). These questionnaires were used to evaluate the subjective experience of sinonasal symptoms, nasal obstruction, and vocal handicap, respectively, in the participants' native language. Preoperatively, all patients underwent a nasal sinus CT scan, which was evaluated for severity using the Lund-Mackay (LM) score. The surgical intervention varied among participants: some underwent isolated maxillary sinus surgery, others had unilateral procedures, and a subset received complete "full-house" sinus procedures. Additional surgical steps such as septoplasty and partial inferior turbinectomy were performed where clinically indicated. The type of procedure and any additional procedures performed were documented and collected for analysis.

Voice feature analysis

Recorded voices were processed for feature extraction using both Praat-parselmouth (for phonetic and acoustic analysis) and Librosa (for signal analysis) libraries in Python. Key voice features extracted included Mel-frequency cepstral coefficients (MFCCs) such as mean, variance, centroid, and flatness, as well as formant frequencies (in Hz and dB). The pre-processed segments were analyzed to capture various voice parameters that could indicate any effect of sinonasal improvements on voice production. Praat-parselmouth provided formant analysis, while the Librosa library aided in extracting spectral features such as MFCCs and spectral centroid, facilitating a robust analysis of voice quality.

Statistical analysis

Statistical analysis was performed using Jamovi software (version 2.5.3) on OSX and Python (version 3.12). Python libraries utilized for statistical analysis included Pandas for data management and preparation, SciPy for parametric and non-parametric statistical tests to assess differences in pre- and post-operative outcomes, and Matplotlib & Seaborn for the creation of visualizations for data representation, including boxplots for the distribution of voice features, scatterplots for correlations, and paired data visualizations. Both parametric and non-parametric tests were used where appropriate, depending on the distribution characteristics of the variables. Significance was set to $p = 0.05$, The 13 mean MFCC values were assessed independently; significance threshold was adjusted accordingly. Significant changes between pre- and post-operative assessments were identified, particularly focusing on differences in SNOT-22, NOSE, and VHI-10 scores, as well as changes in acoustic voice parameters.
A power analysis was conducted for the primary acoustic outcome (MFCC13-mean). To detect a large effect size (Cohen's $d = 0.8$) with a two-tailed paired t-test, assuming $\alpha = 0.05$ and power

= 0.80, a minimum of 15 participants was required. The final sample of 23 patients thus provided adequate statistical power to detect clinically meaningful within-subject differences.

Results

Study population

A total of 38 patients who underwent functional endoscopic sinus surgery (FESS) were initially enrolled in the study. Of these, 14 patients were lost to follow-up due to early postoperative return (within 10–14 days) or failure to attend scheduled follow-up visits. An additional patient was excluded due to a prior cerebrovascular accident (CVA), which precluded completion of the required assessments. The final analysis comprised 23 patients who completed both preoperative and postoperative (approximately one month post-surgery) voice recordings and questionnaire assessments. The mean age of the cohort was 42.27 ± 18.02 years, and the group consisted of 13 females (56.52%). Four participants (17.39%) had a history of previous sinus surgery. Preoperative evaluation revealed a mean SNOT-22 score of 59.91 ± 22.58, a NOSE score of 14.22 ± 5.07, and a VHI-10 score of 8.13 ± 7.77, indicating significant sinonasal and voice-related symptoms. Post-operative scores demonstrated substantial improvement, with mean SNOT-22, NOSE, and VHI-10 scores decreasing to 23.54 ± 17.96, 4.91 ± 4.39, and 2.68 ± 5.59, respectively. The Lund-Mackay scores for the left and right sinuses were 4.74 ± 3.52 and 4.39 ± 3.77, respectively. Data are summarized in Table S1.

Questionnaire outcomes

Patient-reported outcomes, assessed using the SNOT-22, NOSE, and VHI-10 questionnaires, demonstrated significant improvements following FESS. The median reduction in SNOT-22 was 8.5 ($p < 0.01$), indicating substantial relief from sinonasal symptoms. The NOSE score showed a median reduction of 12.5 ($p < 0.01$), reflecting improved nasal patency. Voice-related quality of life, measured by the VHI-10, exhibited a significant improvement, with a median reduction of 5.0 ($p < 0.01$).

Table S1. Descriptive data on independent validation cohorts (n=23).

	Pre-op	Post-op
Age	42.27 ± 18.02	
Female	13 (56.52%)	
History of sinus surgery	4 (17.39%)	
SNOT-22	59.91 ± 22.58	23.54 ± 17.96
NOSE	14.22 ± 5.07	4.91 ± 4.39
VHI-10	8.13 ± 7.77	2.68 ± 5.59
Left Lund-Mackey score	4.74 ± 3.52	
Right Lund-Mackey score	4.39 ± 3.77	

Source features and formants

The analysis of source features and formant frequencies revealed significant changes following sinus surgery. Jitter showed a numerical decrease (0.0126 to 0.0110), but this did not reach statistical significance in the individualized analysis ($p = 0.23$, Cohen's $d = -0.32$). Shimmer showed a significant reduction (0.0847 to 0.0652, $p < 0.00001$, Cohen's $d = -0.40$), suggesting potential improvements in vocal stability, though not necessarily tied to supraglottic resonance alone. HNR increased (15.91 dB to 17.71 dB, $p < 0.00001$, Cohen's $d = 0.37$). There was no significant shift in formant frequencies, though small, non-significant changes were observed.

Mel-frequency cepstral coefficients (MFCCs)

Statistically significant changes were observed in several MFCC parameters post-surgery, indicating alterations in spectral features of the voice. MFCC4-mean ($p = 0.002$), MFCC10-mean ($p = 0.008$), and MFCC13-mean ($p < 0.001$) demonstrated the most robust changes. These coefficients reflect key acoustic variations, with MFCC13-mean emerging as the most sensitive indicator of improved resonance and vocal quality after FESS.

Spectral flatness

Spectral flatness exhibited a significant change following surgery ($p < 0.05$), suggesting modifications in the harmonic structure of the voice.

Partial vs. bilateral disease

When comparing the pre- and post-surgery delta changes between patients with bilateral and partial (unilateral) sinonasal disease, distinct trends emerged across the significant acoustic features. Patients with bilateral disease exhibited more consistent and pronounced changes in Spectral Flatness and MFCC4-mean, potentially reflecting the broader impact of bilateral sinus obstruction on nasal resonance and airflow. Conversely, patients with unilateral disease demonstrated greater variability, particularly in MFCC13-mean, which showed significant shifts in both groups but with a slightly larger average delta in the unilateral group.